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Space systems — Flywheel module design and testing

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Foreword

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work. ISO collaborates closely with the International Electrotechnical Commission (IEC) on all matters of electrotechnical standardization.

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ISO 21648 was prepared by Technical Committee ISO/TC 20, *Aircraft and space vehicles*, Subcommittee SC 14, *Space systems and operations*.

Introduction

Flywheels are mechanical devices that store kinetic energy in a rotating mass. A simple example is the potter's wheel, which was widely used by people in ancient times. The first use of such devices dates from between 3500 and 3000 BC. According to archeological evidence, these early flywheels were built from wood, stone and clay. One type of potter's wheel was the a rim made from a unidirectional material (bamboo) wound in the hoop direction and embedded in a matrix (clay). This design option is clearly a foreshadowing of the later use of composites for their inherent strength and lightweight nature.

It was, however, only since the 1970s that the use of flywheels as energy storage systems has gained some serious attention from energy researchers due to the constant threat of a shortage of fossil fuel supplies. Today, a typical flywheel energy system consists of a flywheel rotor, a supporting device (magnetic bearing), a charge/discharge device (motor/generator), and a safety containment (housing). For space applications, due to weight constraints, the use of a bulky safety containment system may not be a desirable design. Thus, from a safety point of view, the design of flywheel energy systems must concentrate on reliability and longevity.

Current flywheel energy storage technology is made possible by the use of high-strength, carbon-fiber-based composite materials in the rotor. Flywheel energy storage systems are designed to both control spacecraft attitude and to store energy, functions which have historically been performed by two separate systems. The stored energy is needed for the dark portions of the orbit when Earth's shadow makes solar power unavailable for spacecraft. For many spacecraft, flywheels offer the potential to significantly reduce weight and extend service life. However, use of composite materials, coupled with variations in design approaches and demanding operating conditions, combine to present certification challenges for the rotor assemblies.

This International Standard establishes the design, analysis, material selection and characterization, fabrication, test and inspection of the flywheel module in a flywheel. To implement these requirements will assure a high level of confidence in achieving safe operation and mission success.

Space systems — Flywheel module design and testing

1 Scope

1.1 Purpose

This International Standard establishes the design, analysis, material selection and characterization, fabrication, test and inspection of the flywheel module (FM) in a flywheel used for energy storage and/or attitude control in manned or unmanned space systems. These requirements, when implemented on a FM will assure a high level of confidence in achieving safe operation and mission success.

1.2 Field of Application

The requirements set forth in this International Standard are the minimum requirements for FMs in flywheels used in space flight applications. They are specifically applicable to the parts in the flywheel rotor assembly (FRA) including rim, hub and/or shaft, and other associated rotating parts such as the bearings and the motor generator rotor. The requirements are also relevant to the non-rotating parts such as module housing, main suspension assembly (magnetic or rolling element bearings, superconductor bearings or other), motor stator, caging mechanism, and sensors within the module housing, backup bearings, if applicable.

2 Normative references

The following referenced documents are indispensable for the application of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO 21347:2005, *Space Systems – Fracture and Damage Control*

3 Terms, definitions, symbols and abbreviated terms

3.1 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

3.1

“A” basis allowable

mechanical strength value above which at least 99% of the population of values is expected to fall, with a confidence level of 95%

Cf. B-basis allowable (3.4)

3.2

Acceptance tests

required formal tests conducted on hardware items to ascertain that the materials, manufacturing processes, and workmanship meet specifications

3.3

Allowable load (stress or strain)

maximum load (stress or strain) that can be accommodated by a structure (material) without rupture, collapse, or detrimental deformation in a given environment. Allowable loads (stress or strain) commonly corresponding to the statistically based minimum ultimate strength, buckling strength and yield strength as applicable

3.4

“B” basis allowable

mechanical strength value above which at least 90% of the population of values is expected to fall, with a confidence level of 95%

3.5

Catastrophic failure

structural failure event due to the rotor separation, or the rupture or collapse of other FRA components or assembly

3.6

Composite material

combination of materials which differ in composition or form on a macro-scale

NOTE The constituents retain their identities in the composite, i.e., they do not dissolve or otherwise merge completely into each other although they act in concert. Normally, the composites can be physically identified and exhibit an interface between one another.

3.7

Damage tolerance

ability of material/structure to resist failure due to the presence of flaws for a specified period of unrepaired usage

3.8

Damage tolerance life

required period during which a part of a FM, even containing a large undetected crack, is shown by analysis or testing, not fail catastrophically in the expected service load and environment

3.9

Damage tolerance analysis/or testing

analysis/or testing that is used to demonstrate damage tolerance life

NOTE For metallic parts, this type of analysis is also referred to as safe-life analysis.

3.10

Design safety factor

multiplying factor to be applied to the limit load and/or maximum expected operating speed (MEOS)

3.11

Fatigue life

number of load cycles experienced in service (i.e., flight loads, ground test loads and charge/discharge cycles) that a defect-free part in a FM can sustain before failure of a specified nature could occur

3.12

Flaw

local discontinuity in a structural material

EXAMPLES crack, delamination or void.

3.13

Flight-like test article

test article that is built in accordance with a fabrication process identical to the flight hardware

3.14**Flywheel module****FM**

the assembly of mechanical parts of which support and spin the flywheel rotor assembly (FRA) and houses the appropriate sensors, rotor support systems and motor that with the appropriate avionics suite and software can act as a stand alone functional flywheel units

NOTE A FM typically includes the housing, main suspension system (magnetic or rolling element bearing, superconductor bearings), motor stator, caging mechanism, sensors and backup bearings if applicable.

3.15**Flywheel rotor assembly****FRA**

assembly in a flywheel that consists of rim, shaft and/or hub, bearings, motor generator rotor and other associated parts that rotate under normal operation

3.16**Fracture critical part**

classification of a part for manned space systems, which assumes that fracture or failure of that part resulting from occurrence of a crack-like defect would create a catastrophic hazard. Such classification is required on components unless it can be shown otherwise, i.e., if the part (and subsequent parts it could fail) can be shown to be contained; or of low released energy; or if the part is failsafe; or if there is only a remote possibility of significant crack growth on the part to begin with

3.17**Fracture control**

application of design philosophy, analysis method, manufacturing technology, quality assurance, and operating procedures to prevent premature structural failure caused by the propagation of cracks or crack-like flaws during fabrication, assembly, testing, transportation and ground handling and service

3.18**Fracture mechanics**

engineering discipline that describes the behavior of cracks or crack-like flaws in materials under stress

3.19**Fracture toughness**

generic term for measurements of resistance to extension of a crack

3.20**Impact damage**

damage in a non-metallic part within the FM that is caused by an object striking on the part or the part striking on an object

3.21**Impact damage tolerance**

the ability of the fracture critical non-metallic parts in the FM to resist strength degradation due to the impact damage event

3.22**Initial flaw size**

maximum flaw size, as defined by nondestructive evaluation (NDE), that is assumed to exist for the purpose of performing a damage tolerance (safe-life) analysis or testing

3.23**Key process parameter****KPP**

critical process parameters that affect design and product characteristics

3.24

Life factor

factor by which the service life is multiplied to obtain total fatigue life or damage tolerance life. It is often referred to as a scatter factor that is normally used to account for the scatter of material's fatigue or crack growth rate data. It also may account for the dispersion of loading spectra parameters and other uncertainties when appropriate

3.25

Limit load

maximum expected external load or combination of loads that a rotating part can experience during the performance of specified mission in specified environments

NOTE When a statistic estimates is applicable, the limit load is that load not expected to be exceeded at 99% probability with 90% confidence.

3.26

Margin of safety

MS

$$MS = \{ \text{Allowable Load} / (\text{Limit Load} \times \text{Design Safety Factor}) \} - 1$$

NOTE Load may mean stress or strain.

3.27

Maximum expected operating speed

MEOS

maximum spinning speed that a part in a FM is expected to experience during its normal operation.

NOTE MEOS is synonymous with limit speed.

3.28

Maximum design speed

MDS

the highest possible operating speed based on a combination of credible failures. It is required for some manned systems to accommodate any combination of two credible failures that will affect speed

3.29

Nondestructive evaluation

NDE

process or procedure for determining the quality or characteristics of a material, part, or assembly without permanently altering the subject or its properties

NOTE In this document, this term is synonymous with non-destructive inspection (NDI), and non-destructive testing (NDT).

3.30

Operating environments

all environments experienced during service life of the FM

3.31

Proof spin test

spin test that is run on a flight FM at a pre-selected spinning speed that is higher than MEOS

3.32

Qualification tests

required formal tests used to demonstrate that the design, manufacturing, and assembly have resulted in hardware conforming to specification requirements

NOTE Qualification test is synonymous with certification test.

3.33**Service life**

period of time (or cycles) that starts with item inspection after the manufacturing and continue through all testing, handling, storage, transportation, normal operation, refurbishment, re-testing, and reuse that may be required or specified for that part

3.34**Stress-rupture life**

time during which the composite maintains structural integrity considering the combined effects of stress level(s), time at stress level(s), and associated environments

3.35**Touchdown bearings**

bearings required to act as the rotor suspension system in the non-operating mode and/or the backup suspension system in the operating mode during main suspension system failure

3.36**Touchdown event**

event which can occur with FMs supported on magnetic bearings whereby during normal operation the rotor is unexpectedly forced onto its touchdown bearings due to malfunction of magnetic bearings or overload or other anomaly

3.37**Ultimate load**

product of the limit load and the design ultimate safety factor

NOTE

It is the load that the parts in a FM must withstand without catastrophic failure in the expected environment.

3.38**Visual damage threshold****VDT**

an impact energy level shown by test(s) that creates an indication that is detectable by a trained inspector using an unaided visual technique

3.2 Symbols and abbreviated terms

a	Crack size
ATP	Acceptance Test Program
CT	Computer Tomography
da/dN	Fatigue Crack Growth Rate
FM	Flywheel Module
FMECA	Failure Modes and Criticality Analysis
FRA	Flywheel Rotor Assembly
I_p	Polar Mass Moment of Inertia
I_t	Transverse Mass Moment of Inertia
K_{IC}	Plane Strain Fracture Toughness
K_{ISCC}	Stress Intensity Threshold for Stress-Corrosion Cracking

KPP	Key Process Parameter
MDS	Maximum Design Speed
MEOS	Maximum Expected Operating Speed
N	Number of cycle
MoS	Margin of Safety
MPE	Maximum Predicted Environment
MRB	Material Review Board
NDE	Non-destructive Evaluation
NDI	Non-destructive Inspection
NDT	Non-destructive Testing
PSD	Power Spectral Density
RPM	Revolution per Minute
SP	Specification Performance
S-N	Stress Vs Life
ε -N	Strain Vs Life
T _g	Glass Transition Temperature
VDT	Visual Damage Threshold

4 General requirements

This section presents the general requirements for the design; material selection and characterization; fabrication and process control; quality assurance; repair and refurbishment; and storage for the parts in the FM. Most of the requirements are specified for both manned and unmanned space systems.

NOTE Requirements primarily applicable to manned space systems are specifically stated and identified by an asterisk (*) next to the section title or the beginning of the respective paragraph(s).

4.1 Design requirements

The general design requirements for the parts in the FM are delineated in the following sections.

4.1.1 System analysis

A thorough system analysis of the flywheel shall be used to establish design parameters for the FM.

4.1.1.1 System impact threat analysis*

For fracture critical non-metallic parts in the FM used in manned space systems, a system threat analysis shall be conducted to provide information for preparing the damage control plan. The threat analysis shall document the conditions (source and magnitude of threat) under which impact damage can occur.

4.1.1.2 Failure modes effects and criticality analysis

A Failure Modes Effects and Criticality Analysis (FMECA) shall be conducted. This analysis is used to systematically evaluate and document, by item failure mode analysis, the potential effect of each functional or hardware failure on mission success, personnel and system safety, system performance, maintainability, and maintenance requirements. Each potential failure is ranked by the severity of its effect in order that appropriate corrective actions may be taken to eliminate or control the high-risk items.

4.1.2 Loads, speeds and environments

The anticipated load, speed and associated temperatures throughout the service life of the flywheel shall be used to define the design load/temperature profile for the parts in the FM. Other environmental effects (radiation, corrosive atmosphere, vacuum, etc.) pertinent to the structural strength and life of these parts shall be considered, as appropriate.

Throughout this document, limit load and maximum expected operating speed, MEOS, are used as the baseline load and speed.

NOTE: The term maximum design speed (MDS) can be used for design and testing of FMs. The basic difference between MDS and MEOS is the degree of consideration of potential credible failure within a FM, and resultant effects on speed of the FM during system operation. MDS is associated with manned systems, and is based on the worst-case combination of two credible system failures. The criteria to be used for the determination of speed for a given design and application must be clearly established by the contracting parties.

4.1.3 Strength

All parts in the FM shall possess adequate strength to preclude detrimental deformation at corresponding limit loads in the expected test and operating environments throughout their respective service lives. All parts in the FM shall also possess adequate strength to preclude catastrophic failure at design ultimate load.

4.1.3.1 Local yielding

Local yielding in a FM part due to secondary or peak stresses shall be acceptable only if all of the following are satisfied:

- a) the structural integrity of the part shall be demonstrated by adequate analysis and/or test;
- b) there shall be no detrimental deformation which affects FM function or stability: and
- c) the service life requirements are met.

4.1.4 Static stiffness

All parts in the FM shall possess adequate stiffness to preclude detrimental deformation at corresponding limit loads in the expected test and operating environments throughout their respective service lives. All parts shall also possess adequate stiffness to preclude collapse at design ultimate load.

4.1.5 Rotor dynamics

This set of requirements shall be applied to FRAs in FMs. Natural frequencies and critical speeds shall not be of a type or of a frequency response that would be deleterious to the safety and operation of the flywheel system. Established and proven methods shall be employed to minimize the number of lateral critical speeds and natural frequencies within the operating range, and particularly those that are characterized by a higher level of strain energy within the rotor (e.g. bending modes of operation). Shaft bending critical speeds in the operating speed range shall be avoided if possible, but if present it shall be demonstrated by test to be safe to operate at or through the critical speeds. Stability of the rotor to torsion, axial and lateral excitations (e.g.

imbalance, motor torsion oscillations, seismic events, touchdown bearing impact, etc.) shall be maximized through the application of isolation, damping and/or related means to permit stable rotor performance.

4.1.6 Thermal

Thermal effects, including temperatures, thermal gradient, thermal stresses and deformations, and changes in the physical, mechanical, and the glass transition temperature, T_g , of the composite materials of construction, shall be considered in the design of all parts in the FM. These effects shall be based on temperature extremes in accordance with 4.1.2.

4.1.7 Static strength margin of safety

For all parts in the FM, the margin of safety (MS) shall be calculated by using material allowable strengths and the design safety factor. For metallic and composite parts, the minimum design ultimate safety factor shall be 1.5. To allow for local yielding in metallic parts, the yield design safety factor shall be 1.1. For bonded interfaces and ceramics parts, the minimum design ultimate safety factor shall be 2.0. All MS's shall be positive for all applicable loading conditions such as launch, landing, and touchdown event.

4.1.7.1 Manned space systems*

For manned space systems, MS calculations for fracture critical parts shall use A-basis allowables. Otherwise B-basis allowables may be used. These allowables shall be derived from samples of size and shape representative of manufacturing to the greatest degree practical. Where properties are not attained from specimens tied closely to the FM geometry and manufacturing processes, a smaller number of specimens at the subcomponent level shall be tested to anchor these properties and account for size, shape and residual stress effects. The speed range used in this analysis shall encompass the MEOS, unless otherwise specified.

4.1.7.2 Unmanned space systems

For unmanned space systems, MS calculations may use B-basis allowables. These allowables shall also be derived from samples of size and shape representative of manufacturing to the greatest degree practical. Where properties are not attained from specimens tied closely to the FM geometry and manufacturing processes, a smaller number of specimens at the subcomponent level shall be tested to anchor these properties. The speed range used in this analysis shall encompass the MEOS, unless otherwise specified.

4.1.8 Fracture control*

4.1.8.1 Fracture critical selection criteria

Unless otherwise specified, rotating parts that meet containment requirements specified in 4.1.8.1.1 are not considered to be fracture critical.

Parts are fracture critical if it is credible that cracks in the part could lead to a catastrophic failure. For composite materials, the term crack also includes delamination, defects due to manufacturing, impact damage and in-service mechanical damage.

All fracture critical parts shall meet the damage-tolerance life requirements of 4.1.8.2. For composite fracture critical parts, the impact damage requirements of 4.1.8.3 shall also be satisfied.

4.1.8.2 Containment

For a rotating part to be classified as a contained part, it shall meet the following requirements:

- a) it is clearly contained in associated housing/enclosure, etc.; and
- b) it can be shown that the failure of the part will not cause a catastrophic hazard.

Analyses or tests must be performed where there is uncertainty regarding containment of fragmented pieces.

4.1.8.3 Damage-tolerance Life

In a manned space system, all fracture critical metallic and ceramic parts of the FM shall have adequate damage-tolerance life. It is required that the largest undetected crack (consistent in size with the proof test limits or sensitivity of the nondestructive evaluation (NDE)) applied which could exist in the fracture critical part will not grow to failure when subjected to cyclic and sustained loads in a specified number of service lifetimes. These loads shall be determined in accordance with requirement in 4.1.2. Unless otherwise specified, the required damage-tolerance life is 4 x service life.

4.1.8.4 Impact damage tolerance

In a manned space system, the residual strength of a fracture critical composite part in the FM shall not be degraded below its ultimate load requirement after it has been subjected to the greater of a system threat analysis energy level or VDT level impact.

A part having a static strength factor of safety of 4.0 or greater is not required to meet this impact damage tolerance requirement.

4.1.9 Fatigue life

All non-fracture critical parts in the FM in a manned space system, or all parts in the FM used in unmanned space systems, shall have adequate fatigue life in order to achieve mission success. Unless otherwise specified, fatigue life shall be 4 x service-life with no induced damage or defects.

4.1.10 Time dependent behavior

All parts in the FM shall be designed to preclude excessive cumulative strain and/or stress redistribution as a function of time stemming from time dependent material behavior (e.g. creep, relaxation, and thermal recovery), which would result in rupture, detrimental deformation/delamination, or collapse (e.g. buckling) during its service life. Unless otherwise specified, time dependent deformation analysis and/or testing shall account for durations of 4 x service life.

4.1.11 Stress-rupture life

The composite parts in the FM shall be designed to meet the service life requirement including the time that the FM is under sustained load. There shall be no credible composite fiber stress-rupture failure modes based on stress-rupture data for a specified probability of survival. The probability of survivor shall be selected by the user for the intended application.

Unless otherwise specified, the minimum probability of survival associated with catastrophic failure shall be 0.999.

4.1.12 Corrosion and stress corrosion control and prevention

Degradation of the parts in the FM due to the following factors shall be considered:

- a) Corrosive or incompatible environments
- b) Galvanic corrosion resulting from the use of incompatible materials
- c) Stress-corrosion cracking

4.1.13 Outgassing

The effects of potential material outgassing on system performance, material properties or detrimental contamination of the flywheel system or its surroundings shall be considered in the design and selection of materials.

4.2 Materials requirements

4.2.1 Metallic materials

4.2.1.1 Metallic material selection

Material selection for metallic parts of the FM shall be based on known material strengths and fatigue characteristics consistent with the overall system requirements.

*For manned space systems, fracture toughness and crack growth rates (da/dN) for all metallic fracture critical parts shall be considered. Metallic materials which have a K_{ISCC} less than 60% of material's K_{IC} in the expected operating environment shall not be used.

4.2.1.2 Metallic material evaluation

The selected metallic materials shall be evaluated with respect to material processing, fabrication methods, manufacturing operations, refurbishment procedures and processes, and other factors which affect the resulting strength and fracture properties of the material in the fabricated as well as the refurbished configurations.

Materials which are susceptible to stress-corrosion cracking or embrittlement mechanisms such as hydrogen embrittlement shall be evaluated by performing sustained load fracture tests when applicable data are not available.

4.2.1.3 Metallic material characterization

The allowable mechanical properties and fracture properties of all metallic materials selected for metallic parts shall be characterized in sufficient detail to permit reliable and high confidence predictions of their structural performance in the expected operating environments, unless these properties are available from reliable sources.

Where material properties are not available, they shall be characterized by tests. Uniform test procedures shall be employed for determining material strength and fracture properties as required. These procedures shall conform to recognized standards. The test specimens and procedures utilized shall provide valid test data for the intended application. Sufficient tests shall be conducted so that meaningful nominal values of fracture toughness, fatigue data, and crack growth rate data corresponding to each alloy system, temper, product form, thermal and chemical environments and loading spectra can be established to evaluate compliance with strength, damage-tolerance life and/or fatigue requirements.

4.2.2 Composite materials

4.2.2.1 Composite material selection

Composite materials used for a part in the FM shall be selected on the basis of environmental compatibility, material strength/modulus, fatigue, and stress-rupture properties. The effects of fabrication process, temperature/humidity, load spectra, and other conditions, which may affect the strength and stiffness of the material in the fabricated configuration, shall also be included in the rationale for selecting the composite materials.

4.2.2.2 Composite material evaluation

The materials selected for a composite part in the FM shall be evaluated with respect to the material processing, fabrication methods, manufacturing operations, and processes, operating environments, service life and other pertinent factors which affect the resulting strength and stiffness properties of the material in the fabricated configurations.

4.2.2.3 Composite material characterization

The properties of the composite materials selected shall be characterized in their expected operating environments. Test methods employing samples representative of the manufacturing processes involved in FM hardware fabrication and accounting for residual stresses shall be employed for determining material properties as required. The test specimens and procedures utilized shall follow standardized test methods whenever available in order to provide valid test data for the intended application.

Composite material's strength allowables shall be determined from testing of coupon, sub-scale or full-scale composite parts. When sub-scale and coupon data are used in the database, correlation between coupon/sub-scale data and full-scale data shall be established.

4.2.3 Ceramic materials

4.2.3.1 Ceramic material selection

Material selection for ceramic parts of the FM shall be based on known material properties appropriate for the intended application. Key characteristics to be considered shall include fracture toughness, hardness, Weibull parameters, dimensional tolerances, environmental compatibility, elastic properties, thermal properties, electrical properties, surface finish, and surface quality (presence of surface defects caused by impurities). For each type of ceramic component (bearing, magnet, etc.) the temperature and stress distributions shall be determined for both steady-state and transient operating conditions. These data shall then be used in conjunction with accepted life prediction programs to make initial assessments of the probability of survival of the component over its intended lifetime. The minimum acceptable probability of survival will be set on the basis of mission requirements.

4.2.3.2 Ceramic material evaluation

The selected ceramic materials shall be evaluated with respect to material processing, manufacturing robustness, inspection protocols, refurbishment procedures and processes and other factors which affect the functional performance of the material in the fabricated as well as the refurbished configurations. Materials that are susceptible to time or cycle (temperature or stress) dependent failure shall be evaluated by performing stress-rupture and/or cyclic fatigue tests when applicable data are not available.

4.2.3.3 Ceramic material characterization

The mechanical and thermal properties of all ceramic materials selected for FM parts shall be characterized in sufficient detail to permit reliable and high confidence predictions of the operating stresses and temperatures for steady-state and transient conditions. The Weibull and slow crack growth/cyclic fatigue parameters required for prediction of probability of survival must be characterized as well. Potential sources of these data include the material suppliers, technical publications, and established databases.

Where material properties are not available, they shall be characterized by established tests. When possible these procedures shall conform to recognized standards. If no standards exist, the adopted test procedures must be based on the best available methods as defined in the current technical literature. Sufficient tests shall be conducted so that statistically meaningful data corresponding to each material type, manufacturing method, product form and size, thermal and chemical environments and operating spectra can be established to evaluate compliance with strength, safe-life and/or fatigue requirements. Analyses shall be verified by conducting proof tests on ceramic components identical in material, geometry, and manufacturing method to those used in the FM. The proof test conditions shall simulate the worst case operating conditions appropriate

for the component in question (e.g. rolling contact fatigue in the case of ceramic bearings and thermal transients for ceramic magnets).

4.2.4 Polymeric materials

4.2.4.1 Polymer material selection

Polymeric materials used for a part or for joining parts in the FM shall be selected on the basis of environmental compatibility, material strength/modulus, fatigue, creep deformation/relaxation, stress-rupture properties, and suitability as an adhesive, as dictated by the application. The effects of fabrication process, temperature/humidity, load spectra, and other conditions, which may affect the strength, stiffness, and dimensional tolerance of the material in the fabricated configuration, shall also be included in the rationale for selecting the polymeric materials.

4.2.4.2 Polymer material evaluation

The materials selected for a polymeric part in the FM shall be evaluated with respect to the material processing, manufacturing operations, and processes, operating environments, service life and other pertinent factors which affect the resulting strength, stiffness, and dimensional tolerance properties of the material in the fabricated configurations.

4.2.4.3 Polymer material characterization

The properties of the polymeric materials selected shall be characterized in their expected configurations and operating environments. Test methods employing samples representative of the manufacturing processes involved in FM hardware fabrication shall be employed for determining material properties as required. The test specimens and procedures utilized shall follow standardized test methods whenever available in order to provide valid test data for the intended application.

Polymeric material's strength allowables shall be determined from testing of coupon, sub-scale or full-scale composite parts. When sub-scale and coupon data are used in the database, correlation between coupon/sub-scale data and full-scale data shall be established.

4.3 Fabrication and process control

The design of the parts in the FM shall employ well-characterized fabrication processes and procedures. The fabrication process for parts in the FM shall be a controlled documented process.

Proven processes and procedures for fabrication and repair of the metallic and ceramic parts in the FM shall be used to preclude damage or material degradation during material processing and manufacturing operations. In particular, special attention shall be given to ascertain that the thermal treatment, machining, drilling, grinding and other operations are within the state-of-the-art and are appropriate for the application.

*For manned space systems, the fracture toughness, mechanical and physical properties shall be within established design limits after exposure to the intended fabrication processes. Fracture control requirements and procedures shall be defined in applicable drawings and process specifications. Detailed fabrication instructions and controls shall exist to ensure proper implementation of the fracture control requirements.

Incorporated materials shall have certifications, which demonstrate acceptable variable ranges to ensure repeatable and reliable performance. The fabrication process shall control or eliminate detrimental conditions in the fabricated article.

An inspection plan shall be developed per 4.4.1 to identify all key process parameters (KPP), essential for verification. In-process inspection or process monitoring shall be used to verify the setup, and the acceptability of critical parameters during the fabrication process.

4.4 Quality assurance

A quality assurance or inspection program, based on a comprehensive study of the product and engineering requirements shall be established to assure that the necessary NDE and acceptance proof spin tests are performed effectively. The program shall ensure that no damage or degradation has occurred during material processing, fabrication, inspection, acceptance tests, shipping, storage, assembly and operational use and refurbishment; and that defects which could cause failure are detected or evaluated and corrected. As a minimum, the following shall be included in the quality assurance program. Quality assurance data for all parts of the FM shall be maintained throughout the service life.

4.4.1 Inspection plan

An inspection master plan and sample plan shall be established prior to start of fabrication. The plan shall specify appropriate inspection points and inspection techniques for use throughout the program, beginning with material procurement and continuing through fabrication, assembly, acceptance proof spin test, shipment, assembly and operation, as appropriate. In establishing inspection points and inspection techniques, consideration shall be given to the material characteristics, fabrication processes, design concepts, corrosion control and accessibility for inspection of defects.

4.4.2 Inspection techniques

*For manned space systems, the inspection techniques selected for metallic parts shall have the capability to determine the size, geometry, location and orientation of a crack or a crack-like defect. Inspection techniques, such as dye penetrant, magnetic particle, eddy current, radiography, and ultrasound, shall be used for detecting cracks as appropriate. Other NDE techniques used shall have a demonstrated 90% probability of detection at a 95% confidence level.

The inspection techniques for composite materials shall include visual inspection performed in conjunction with appropriate state-of-the-art NDE techniques. Inspections shall be performed to look for non-uniform or broken fibers, delaminations, fiber wrinkles and waviness, dry fibers (i.e., fuzzing or "brooming"), machining damage, impact damage and uniformity of surface coatings, if applicable. Inspections shall be augmented by use of optical magnification or solvent wipe techniques (i.e., for detection of cracks or delaminations). Proven NDE techniques, such as ultrasound, radiography, thermography, computer tomography (CT), and shearography shall be utilized to identify and characterize critical defects, as appropriate. The appropriateness and capability of the NDE methods selected to detect and characterize critical defects shall be established.

4.4.3 Inspection data

Inspection data for the parts in the FM shall be maintained throughout the service life. These data shall be reviewed periodically and assessed to evaluate trends and anomalies associated with the inspection procedures, equipment and personnel, material characteristics, fabrication processes, design concept and structural configuration. The result of this assessment shall form the basis of any required corrective action.

4.4.4 Traceability*

For manned space systems, traceability shall be maintained on all fracture critical parts in the FM throughout their development, manufacturing, testing and service. Serialization shall be required on each fracture critical component and they shall have traceability to material heat treat or composite manufacture/cure lot as a minimum. A log shall be maintained for each part of the FM to record all significant manufacturing assembly processes, load/spin cycles, inspections and tests occurring during the time period from fabrication to the end of service life. Engineering drawings for fracture critical parts shall contain notes, which label the part "fracture critical" and specify the appropriate inspections or flaw screening method to be used.

4.5 Repair and refurbishment

When inspections reveal structural damage or defects exceeding the permissible levels, the nonconforming part shall be assessed by a material review board (MRB) for repair, refurbishment, or replacement. All repairs

and refurbishments shall utilize an approved repair process. All repaired or refurbished hardware shall be verified after each repair and refurbishment by the applicable analysis and/or acceptance test procedure for new hardware to demonstrate their structural integrity and to establish their suitability for continued service.

4.6 Storage requirements

When parts of the FM are put into storage, they shall be protected against exposure to adverse environments (e.g. temperature, humidity, etc.). In addition, they shall be protected against in-service damage, e.g. abrasion, cutting, impact, etc. Critical, environmental conditions shall be recorded.

4.7 Transportation requirements

When the FM parts, or subassemblies or the whole module are transported, they shall be packaged in a manner that will provide protection against damage from physical or environmental sources. These include, but are not limited to, exposure to adverse environmental conditions (e.g. temperature extremes, humidity, water, prolonged exposure to sunlight, etc.), physical impact, vibration and shock during transport. Critical environmental and transportation conditions that pose a threat to the integrity of the FM, such as temperature extremes, excessive vibration or maximum shock loading shall be recorded. The nature of recording (i.e., continuous versus maximums) and parameters to be monitored shall be commensurate with the threat assessment for the method of transportation and the consequences of these transportation parameters on the FM. As a minimum, records shall be kept documenting transportation events, packaging used, method of conveyance, person or company responsible for transport, dates of shipment and receipt, and a written record (possibly including photographs) of the results of a visual inspection of the package and its contents for damage or movement during the transportation process. Any adverse events or observations shall be recorded and assessed for implications on the safety of the FM.

5 Verification requirements

5.1 Design requirements verification

This section is directed towards design requirements verification which is through analysis, test and document review. The purpose of the verification process is to ascertain that:

- a) the design meets the specified requirements and is acceptable for the intended usage; and
- b) parts manufactured to the qualified design meet specified requirements for materials, manufacturing processes, and workmanship.

5.1.1 System analysis verification

The system analysis report shall be reviewed for its adequacy.

5.1.1.1 System impact threat analysis verification

The system impact threat analysis report which documents the source and magnitude of the impact damage threat shall be reviewed.

5.1.1.2 Failure modes effects and criticality analysis verification

The report that documents the results of the FMECA of a FM shall be reviewed periodically to ensure that the analyses were performed and are adequate.

5.1.2 Loads, speeds and environments verification

The anticipated loads and associated temperature and other environments shall be documented and reviewed for adequacy.

5.1.3 Strength verification

Test results of the acceptance proof spin test specified in 5.3.2 and ultimate load test as specified in 5.2.9 shall be used to verify the strength requirements.

5.1.4 Static stiffness verification

Stress analysis results shall be used for analytical verification of static stiffness requirements. Test results of the acceptance proof spin test specified in 5.3.2 and ultimate load test as specified in 5.2.9 shall be used to verify the stiffness requirements.

5.1.5 Rotor dynamics verification

Rotor dynamics requirements as specified in 4.1.5 shall be verified through analysis and/or test. The following are specific verification requirements:

- a) verify through analysis that the rotor assembly's polar mass moment of inertia to transverse mass moment of inertia ratio, I_p/I_t , is outside the range of 0.8-1.2 unless it is verified through test that the rotor can run stably at all intended speeds inside this range; and
- b) verify through test the zero speed free-free rotor modes on the rotor assembly via suspended rap tests to check accuracy of analysis model(s).

For FRA suspended on magnetic bearings, the following verification requirements shall be met:

- a) verify through analysis that the rotor assembly's first forward whirl bending-shaft critical speed is above $1.25 \times \text{MEOS}$ on frequency assuming the free-free support case unless it is verified through test that the rotor can run stably near a bending shaft resonance or through such a resonance; and
- b) verify through analysis that the rotor maintains $1.25 \times \text{MEOS}$ on bending shaft critical speed when on backup bearings (touchdown event case) using appropriate bearing stiffness values, unless it is verified through test that the rotor can operate stably near or through such a resonance on backup bearings in a touchdown event.

For rotor assemblies suspended on mechanical bearings during normal operations, the following verification requirements shall be met:

- a) verify through analysis that the rotor assembly's first shaft-bending critical speed is $1.20 \times \text{MEOS}$ if dampers which significantly suppress shaft bending mode vibration are incorporated; and
- b) verify through analysis that the rotor assembly's first shaft bending critical speed is $1.15 \times \text{MEOS}$ if no dampers are used, unless it is verified through test that the rotor can run stably with less margin from a bending shaft resonance or through such a resonance.

Rotor dynamics analyses shall be performed using appropriate rotor dynamics code or finite element code that accounts for cross coupling and gyroscopic effects.

5.1.6 Thermal verification

Thermal requirements shall be verified through thermal analysis and thermal test as specified in 5.3.3.

5.1.7 Static strength MS verification

MS calculations shall be verified by stress analyses supported by test or through run-to-failure testing. The stress analysis of each part in the FM shall be conducted with the assumption that no defects exist in the parts. The analysis shall determine stresses for all load cases in service life especially the combined effects of rotation and flight induced loads. Finite element or other structural analysis techniques shall be used to perform the required stress analysis. For composites, effects of parameters such as winding angles, winding

sequences, shall be assessed. Analysis tools shall be correlated against test results to demonstrate the accuracy of the methodology, and independently verified with industry accepted tools, where practical. The analytical tool verification shall be submitted as part of the stress analysis report when required.

5.1.8 Fracture control verification*

Fracture control requirements shall be verified through analysis and/or test. If a part can be shown by analysis or test to be contained when failure occurs, it is not fracture critical. If it can be shown to be fail-safe or possess low release energy, it is not fracture critical. The final fracture critical parts list shall be reviewed to assure that the selection criteria are met.

5.1.8.1 Containment verification

Containment housing which is part of the FM shall be verified by documented engineering practice where it is clear that containment exists, or it shall be shown by analysis using proven analytical methodology or by test where there is uncertainty concerning the analysis. It must be verified that not only the parts are contained but that the energy released and resulting reaction loads and torques on the containment system do not create a catastrophic hazard in the supporting structure of a space system or in the ground test facility during development, qualification or acceptance tests.

5.1.8.2 Damage tolerance life verification

A damage tolerance life verification shall be conducted on fracture critical metallic and ceramic parts in a FM used in a manned space system. Damage tolerance safe analysis (also referred to as fracture mechanics crack-growth analysis) shall be performed to verify that it meets the damage tolerance life requirements specified in 4.1.8. Undetected crack(s) shall be assumed to be in the critical location(s) and in the most unfavorable orientation(s) with respect to the applied stress and material properties. The size of the crack(s) shall be based on the appropriate NDE technique(s) used in the acceptance tests. Nominal values of fracture toughness and crack growth rate (da/dN) data shall be used in the analysis. If a proof spin test is used to define the limits on initial crack size for damage tolerance life determination, it shall be demonstrated by analysis or test that the proof spin test will ensure the required life is obtained, including effects of: stable crack growth during proof spin test; anomalous behavior of cracks approaching surface boundaries or in welds; and test environments.

Damage tolerance life verification for fracture critical metallic and ceramic parts can be performed by test using a flight-like part, with controlled size of crack(s). Coupons shall be allowed only for metallic parts when the stress field is well defined and the material properties are representative to that of the flight parts. The size and shape of crack(s) must correspond to the detection capability of the NDE to be imposed on the flight part.

Damage tolerance life verification for fracture critical composite parts in the FM used in manned space system shall be performed by test only. Test spectrum shall include all cycles, time, and environments associated with part service life. Accelerated test techniques can be used when proven. Damage tolerance test(s) for fracture critical composite parts shall be performed by using full-scale, flight-like articles, with pre-fabricated crack(s). The term crack, also means delamination, and other mechanical damage induced in service including surface cuts and abrasions except impact damage. Impact damage shall meet the requirements specified in 5.1.8.3. The shape and size of the controlled cracks must be greater than or equal to the detection capability of the NDE imposed on the flight parts.

5.1.8.3 Impact damage tolerance verification*

Testing is the only acceptable method for fracture critical composite parts in the FM to demonstrate impact damage tolerance. Impact damage tolerance is verified when residual strength is shown to not degrade below the design ultimate load. Full-scale articles that are representative of the flight part, with induced impact damage shall be used as the test specimens. Either system threat analysis energy levels or verified VDT energy levels, whichever is greater, shall be used in the determination of impact energy level in the impact damage tolerance tests.

5.1.9 Fatigue life verification

Fatigue life shall be verified for non-fracture critical FM parts by fatigue analysis or test using load/temperature profile defined in accordance with 4.1.2.. Fracture mechanics based damage tolerance analysis/test may be used as a substitute for fatigue analysis/test if mission success requirements warrant it.

5.1.9.1 Fatigue Analysis

When a fatigue analysis is used to verify the fatigue life of a part in the FM, nominal values of fatigue characteristics, including stress- life (S-N) data and/or strain-life (ϵ -N) data of the material shall be used. These data shall be taken from reliable sources. The analysis shall account for the spectra of expected operating loads, and environments. Miner's Rule is an acceptable method for handling variable amplitude fatigue cyclic loading. The limit for accumulated damage shall be 80% of the normal limit.

5.1.9.2 Fatigue test

Test of unflawed specimens to demonstrate fatigue-life of a specific part together with stress analysis is an acceptable alternative to analytical prediction.

When approved by the procuring agency, the fatigue life test does not need to be completed before the scheduled launch.

5.1.10 Time dependent behavior verification

Time dependent deformation of all parts in the FM shall be verified through analysis and/or test using load/temperature profile defined in accordance with 4.1.2. If such deformation is tied to initiation or propagation of crack-like defects in fracture critical parts, damage tolerance (safe-life) verification takes precedence.

If the time dependent deformation is related to initiation or propagation of crack-like defects in fracture critical composite parts, verification must be demonstrated by test of worst-case crack-like defects in the most unfavorable locations where they can be expected to occur. The orientation of crack-like defects shall also be representative of the worst-case condition that can be expected to occur.

5.1.11 Stress-rupture life verification

Stress-rupture life for composite parts in the FM shall be verified by analysis supported by test data using load/temperature profile defined in accordance with 4.1.2.

5.1.12 Corrosion and stress corrosion control and prevention verification

A corrosion control plan for FM parts that are prone to stress corrosion cracking or corrosion due to environment or galvanic effects shall be reviewed for its adequacy.

5.1.13 Outgassing verification

Outgassing levels of FM materials for the specified operating conditions shall be shown by analysis, test or documented engineering practice to be less than the allowable specified. The effects of outgassing on material properties, dimensional characteristics and residual stresses within the FM shall be established and included in the determination of material properties, analytical evaluations and/or experimental validations.

5.2 Qualification tests

Qualification tests shall be conducted either at the part level, the FRA level or the module level. In general, the tests shall be conducted on a single article. Test article configuration and test attachment shall be representative to flight configuration. However, life tests may be conducted on separate article. Any ground testing of the FM requires proper and conservative containment and shielding. Safety precautions shall be

reviewed thoroughly with the responsible authority. As a minimum, the qualification test program shall consist the following tests. Test sequence shall be defined for each project.

- a) Spin test
- b) Specification performance test
- c) Thermal vacuum test
- d) Vibration and shock tests
- e) Mode survey test
- f) Fault tolerance test(s)
- g) Life test
- h) Ultimate load test

5.2.1 Inspection

Inspections shall be performed after each major test to ensure that all hardware conforms to applicable drawings and specifications for functional performance. Criteria for determining acceptance or rejection of items shall be established.

5.2.2 Spin test

Each qualification test article shall be subjected to a spin test as specified in 5.3.2.

5.2.3 Specification performance (SP) test

A SP test (also referred to as functional test) demonstrates that the mechanical and electrical performance of the FM meets the specification requirements plus the desired qualification margin, after exposure to one or more of the environmental conditions predicted during the mission. A SP test may also verify mechanical or electrical ground support equipment compatibility and operation, as well as software algorithms used to command or monitor the performance of the FM. Although a comprehensive performance test is required to verify all specification requirements, it may not be necessary to verify all requirements at each step of the qualification process. Accordingly, it is possible and expected that the complete performance test be performed at the start, end and after critical environmental conditions, but a subset may be sufficient for verifying compliance after specific environmental conditions.

A SP test shall be developed and implemented to evaluate the performance of the FM after each major environmental test to ensure that the performance of the FM has not been affected by the test. The SP test may be different for each environmental test to ensure that those performance parameters expected to be affected are verified. For instance, the SP test could include a cycle to maximum normal operating speed corresponding to one charge-discharge cycle.

A SP test may be performed after the vibration and thermal vacuum tests to assess the impact of each environmental test, although performance tests may be different after each environmental test type. It is also acceptable to complete performance tests only after completion of environmental tests, but there is more risk inherent in this approach.

Essential environmental conditions correspondent to checked operation mode shall be simulated in SP test. Functional checks in the presence of environments can be conducted in other environmental test.

5.2.4 Thermal vacuum test

A thermal vacuum test shall be conducted to demonstrate the ability of the FM perform in the qualification thermal vacuum environment and to endure the thermal vacuum testing imposed on flight FMs during acceptance testing. It also serves to verify the FM thermal design. Thermal vacuum test guidelines are presented in Annex A.

Unless otherwise specified, the qualification test levels and duration are as follows:

- a) Pressure: $\leq 1,0 \times 10^{-4}$ Torr for hardware subjected to space vacuum condition.

NOTE For hardware that is to be enclosed in a hermetically sealed enclosure during service, the vacuum requirement must replicate the design vacuum.

- b) Temperature: 10°C beyond acceptance temperature or -34°C to 71°C (minimum range)

- c) Duration: 6 cycles.

The FM shall remain operational except during the first and last cycle, where the FM turn-off and turn-on shall occur. After the thermal vacuum environmental test the FM shall be inspected. A SP test shall be conducted before and after thermal vacuum test to verify that the FM is capable of withstanding qualification level of this test.

5.2.5 Vibration and shock tests

The FM shall undergo appropriate vibration and shock test(s).

5.2.5.1 Vibration test

A vibration test shall be conducted to demonstrate the ability of the FM to endure the vibration environment of service including, as minimum, the acceptance test, the transportation, launch and in-orbit phases of the mission with the desired qualification margin. Two types of vibration tests shall be conducted as appropriate: sine vibration test and random vibration test. It is acceptable to conduct one type of these tests if peak response at each frequency and cumulative damage envelope both tests. Vibration test guidelines are presented in Annex B.

Unless otherwise specified, the qualification vibration test levels and duration are as follows:

- a) Sine vibration test level: Two octaves/minute unless the sweep rates and dwell time can be based on the persistence of the environment in service use. The vibration levels shall be sufficient to cover the severity of the maximum design levels that shall be at least by 1,4 times higher than maximum predicted environment but shall not induce unphysical response.
- b) Random vibration test level: 3 dB above maximum predicted environment for 2 minutes in each of three orthogonal axes

Test frequency range shall be defined by the users. A SP test shall be conducted before and after vibration tests to verify that the FM is capable of withstanding qualification level vibration tests.

5.2.5.2 Shock test

The shock qualification test demonstrates the capability of the FM to withstand, or if appropriate, to operate in the shock environments imposed by the launch vehicle or spacecraft plus the desired qualification margin, during any phase of the mission.

The FM must be capable of withstanding the shocks associated with firing of pyrotechnic devices on the spacecraft as well as launch vehicle separation shocks, without degradation of performance outside specification requirements. The FM shall be subjected to shock excitation that covers specified shock spectrum. Typical shock spectrum is presented in Figure B-1 in Annex B, which is representative of launch

and early operations conditions such as deployments employing pyrotechnics. The shocks shall be imparted in both directions in all three axes. Unless otherwise specified, the minimum test level and exposure are as follows:

- Level: 3dB above maximum predicted environment (MPE).
- Duration: 3 times the number of shock events.

A SP test shall be conducted before and after all shock tests.

5.2.6 Mode survey test

The mode survey test (or modal survey) shall be conducted at either FRA level or FM level to verify that there are no dynamic modes that will interfere with proper and stable operation and benchmark a baseline dynamic response. The data obtained shall be adequate to define the resonant frequencies for primary modes in the frequency range of interest

5.2.7 Fault tolerance test

Fault tolerance of the FM as documented in FMECA or hazards analysis shall be verified by test. When a FMECA recognizes the criticality of redundant safety features such as touchdown bearings to prevent catastrophic hazards of the FM due to single faults in FM hardware, a test demonstration of these fault tolerant systems shall be conducted, from full speed if necessary, to mimic worst case loads and demonstrate adequacy of the FM. If a backup mechanical bearing system is incorporated in the FM whose failure would create a catastrophic hazard, then full speed touchdown event testing on backup bearings shall be conducted.

The flywheel systems identified through FMECA as critical to preventing catastrophic hazards in the event of single or double system faults shall be tested at the FM unit level unless it can be adequately shown that these systems can be demonstrated in a subsystem test. If, for example, redundant magnetic bearing actuators/windings are incorporated in the FM flight design and are responsible for the safe shutdown of the FM, then a FM test which simulates a failure and switches control over to backup actuators or windings shall be conducted. If mechanical touchdown bearings are incorporated, the performance of a touch down bearing or any similar capture mechanism shall be verified through a qualification level bearing touchdown test.

5.2.8 Life test

A life test shall be conducted to demonstrate that the FM has the ability to operate within specification requirements for the expected life of the mission including ground operations and test as well as in-orbit operation with the expected environmental conditions, plus the desired qualification margin. This test is separate from the safe-life or fatigue test conducted on parts in the FM level. Unless otherwise specified, the test level and duration are as follows:

- Level: The extreme expected environmental level. Unless otherwise specified, the extreme level is the same as in qualification environment tests.
- Duration: 2 times the predicted cycles during service, including ground testing

A SP test shall be conducted after the completion of the life test. At the end of the life test and the SP test, the FM shall be disassembled and inspected for anomalous and wear-out conditions.

5.2.9 Ultimate load test

An ultimate load test shall be conducted on flight-like parts to verify compliance to the design ultimate factor of safety requirements established by this International Standard. The parts in the FM can be qualified on an individual basis or on the assembly basis. The test parts shall be spun up to the minimum design ultimate speed level of $(1,225) \times \text{MEOS}$. The ultimate load test parameters, such as speed and temperature, shall be suitably adjusted to account for the environmental effects on material properties and stress fields to make the test representative of the lowest margin condition. The test article shall be held at the minimum design

ultimate speed for a minimum of (5) minutes. The test article shall not exhibit catastrophic failure at or prior to the end of the 5-minute hold time.

5.3 Acceptance tests

Acceptance tests shall be conducted on every flight FM to verify if its workmanship and performance meet specification requirements. Test configuration and test attachment shall be representative to flight configuration. Any ground testing of the FM or high energy storing parts requires proper safety measures and appropriate containment and/or shielding whenever possible. Safety precautions shall be reviewed thoroughly with the responsible authority. The following tests are required as a minimum in an acceptance test program (ATP). Test sequence shall be defined for each project.

- a) Inspection
- b) Proof spin test
- c) Specification performance test
- d) Thermal vacuum test
- e) Vibration tests
- f) Mode survey test

5.3.1 Inspection

Each part in the flight FM shall be subjected to visual inspection. Tests shall be conducted either at the part level or at the module level. Accept/reject criteria shall be formulated prior to testing. Inspection shall be performed before proof test and mode survey test to ensure that all hardware conforms to applicable drawings and specifications for functional performance. For fracture critical parts, The NDI selected shall be able to detect fracture critical flaws.

5.3.2 Proof spin test

The proof test is a demonstration of the adequacy of the flight FM to meet the requirements of strength and stiffness, and dynamics with the desired margin, when subjected to a spinning environment expected to occur during the service life. It shall be conducted at both the FRA level and the FM level.

The flight FRA and the flight FM shall be operated to proof spin test speed to verify safe operation baseline rotor dynamics. The rotor shall not fail, experience uncontrollable dynamic instability or distort permanently prior to the end of a 10-minute hold time at proof spin speed. As a minimum, the proof spin test speed shall be $1,05 \times \text{MEOS}$. FM shall be operated at the proof spin test speed for the duration of 10 minutes. Time to reach MEOS and return to 0 rpm shall be determined by the capability of the system unless deemed to be important for the unique design. Nevertheless, the cycle time shall be representative of the service cycle time. Temperature during the proof load test shall be consistent with the critical case identified for operation to account for environmental effects on material properties. FM proof spin test shall be conducted after the FRA proof test, with a test spin speed level of $1,1 \times \text{MEOS}$. FM proof spin test can replace the FRA proof spin test if it tests to speeds encompassing $1,1 \times \text{MEOS}$ proof spin test speed requirement and only if:

- a) the facility has adequate safety and containment provisions;
- b) the backup suspension system or other failsafe suspension system is also sized appropriately to safely spin down a rotor spinning at this over-speed condition.

During acceptance proof spin test no part of the FM shall rupture, experience severe damage, or exceed dynamics specifications produced by elastic and/or plastic deformation throughout the full operational speed range. If necessary, the proof spin test parameters, such as speed and temperature, shall be suitably

adjusted to account for the environmental effects on material properties and stress fields to make the proof spin test representative of the lowest margin condition.

5.3.3 Thermal vacuum test

Each flight FM shall be subjected to thermal vacuum testing to verify performance and thermal management in the intended environment. Thermal vacuum acceptance testing shall be conducted in the manner as in the thermal vacuum qualification test as specified in 5.2.4. As a minimum, the acceptance test margin shall be 5° C.

The FM must operate within specification requirements during the thermal vacuum environmental test. After the thermal vacuum environmental test the FM shall be inspected as well as Performance Evaluation Tested to confirm that performance is within the specification requirement.

5.3.4 Vibration tests

Each flight FM shall be subjected to vibration acceptance test to demonstrate the ability of the FM to endure transportation and flight vibration environment in service. Two types of vibration tests shall be conducted as appropriate: sine vibration and random vibration test. It is acceptable to conduct one type of test if peak response at each frequency and cumulative damage can be enveloped by one test.

5.3.4.1 Sine vibration

Each flight FM must be capable of withstanding sine vibration at desirable acceptance level without degradation of performance outside specification requirements. The sweep rate for acceptance testing shall be 4 octaves/minute over the frequency range. Since modal information may be available from this test, it may combine or replace the modal test.

5.3.4.2 Random vibration

Each flight FM must be capable of withstanding random vibration at desirable acceptance level without degradation of performance outside specification requirements. The procedure for the random vibration acceptance test shall be that specified in 5.2.5.1 for the random vibration qualification test. Duration of random vibration test for acceptance shall be 1 minute.

At the end of the random vibration test, a test article survey shall be conducted to compare modes present in the test range to those measured prior to the test to determine changes. An abbreviated performance evaluation test (functional test) shall be performed before and after vibration testing to verify operation.

5.3.5 Mode survey test

A modal test shall be conducted on the flight FM or FRA to verify that the dynamic response is similar to that qualified, and that there are no system dynamic modes that will interfere with proper and stable operation of the FM.

A modal survey test shall be conducted on each flight unit to verify FM modal frequencies are similar to that qualified. The data obtained shall be adequate to define the resonant frequencies for primary modes in the frequency range of interest.

5.3.6 Performance evaluation test

Performance evaluation test shall be conducted on the flight FM to characterize FM level modal signature, verify dynamic modeling parameters and evaluate performance changes after acceptance tests.

A performance evaluation test demonstrates that the mechanical and electrical performance of the FM meet the specification requirements plus the desired acceptance margin, after exposure to one or more of the environmental conditions predicted during the mission. A performance evaluation test may also verify mechanical or electrical ground support equipment compatibility and operation, as well as software algorithms

used to command or monitor the performance of the FM. Although a comprehensive performance evaluation test is required to verify all specification requirements, it may not be necessary to verify all requirements at each step of the acceptance process. Accordingly, it is possible and expected that the complete performance test be performed at the start, end and after critical environmental conditions, but a subset may be sufficient for verifying compliance after specific environmental conditions.

A performance evaluation test shall be developed and implemented to evaluate the performance of the FM after each major environmental test to ensure that the integrity of the FM has not been affected by the test. The performance evaluation test may be different for each acceptance test to ensure that those performance parameters expected to be affected are verified. The performance evaluation test could include a test to maximum normal operating speed corresponding to one charge discharge cycle.

Performance evaluation tests may be different after each acceptance test type. It is also acceptable to complete performance tests only after completion of all acceptance tests, but there is more risk inherent in this approach.

Annex A

(informative)

Thermal vacuum test guidelines

A.1 Purpose

The thermal vacuum test demonstrates the ability of the FM to meet operating and non-operating (including off mode, safe-hold, etc.) requirements under vacuum conditions and temperature extremes which simulate those predicted for flight plus the desired qualification margin for a number of temperature cycles.

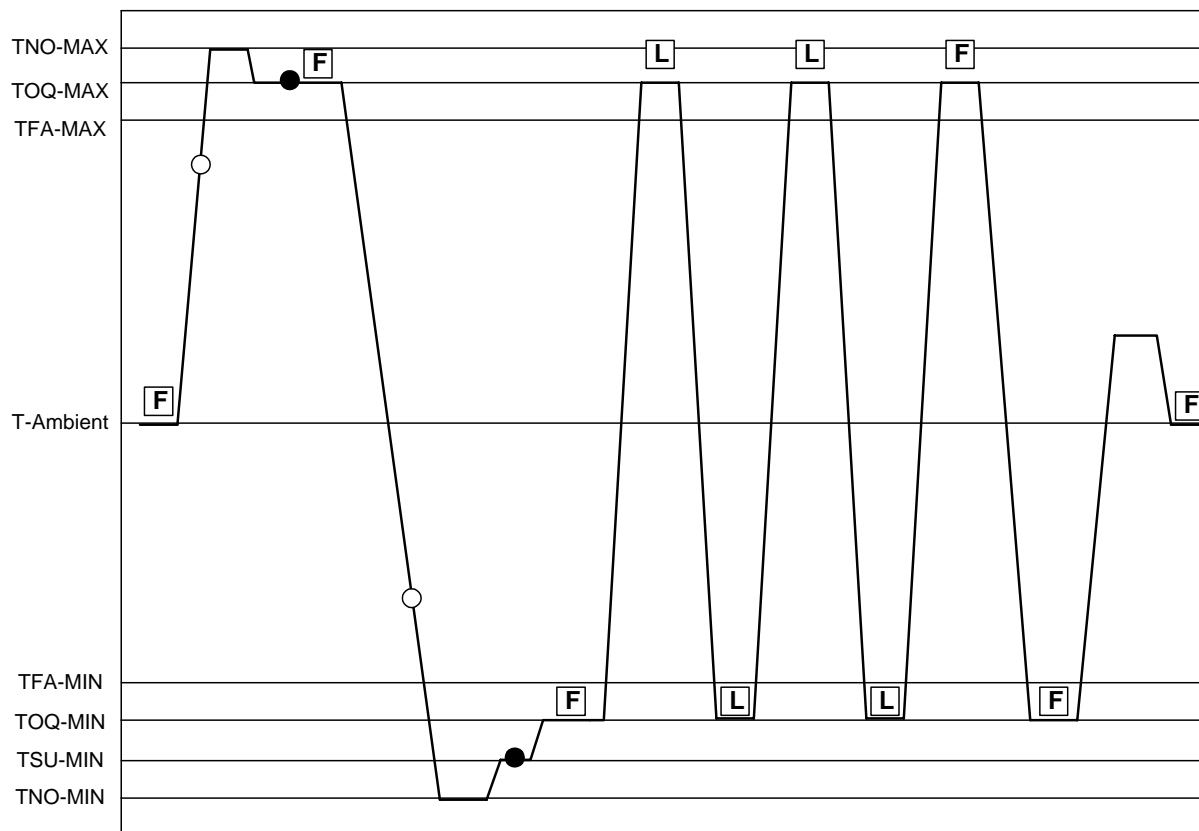
A.2 Test description

The FM should be subjected to thermal vacuum testing to verify performance and adequate thermal management in the intended environment. Thermal vacuum testing should be conducted in a vacuum to the temperature cycle procedures shown for qualification testing below in Figure 2, or to measured values of temperature and vacuum in the intended application including margin for tolerances and uncertainty. Space flight hardware should operate as specified during exposure to the thermal vacuum environment.

Testing should be performed at vacuum conditions $\leq 10^{-4}$ Torr for hardware subjected to space vacuum conditions. For hardware that is to be enclosed in a hermetically sealed enclosure during service, the vacuum requirement must replicate the design vacuum. However, it is important to ensure that the heat transfer path from the unit to a mounting or cold plate provides representative thermal resistance to simulate the flight configuration. An alternate configuration may be acceptable provided that heat flux through the mounting fixture can be measured. However, control of the test unit temperature to flight predictions should be maintained. The FM should be configured in an operational stage during the test and operated for periods during the test as shown in Figure A-1. The FM should be cycled through complete operational cycles as indicated in Figure A-1 including hold periods of at least 10 minutes at maximum operational speed. The temperature environment measured during this period of operation must stabilize below the maximum operating temperature of the FM.

Thermal vacuum cycling should follow the temperature profile shown below in Figure A-1. Once the required vacuum has been achieved, the temperature should transition between the temperature extremes at an average rate of between 1°C per minute and 3°C per minute. Temperature margins should be imposed to account for uncertainty in analysis and to provide a margin of safety in the design. A 5°C margin should be added to max predicted operating temperature and an additional margin of 10°C should be added for qualification testing.

The FM must operate within specification requirements during the thermal vacuum environmental test. After the thermal vacuum environmental test the FM should be inspected using some form of nondestructive inspection (NDI) technique as well as a performance evaluation (function) test to confirm that performance is within the specification requirements.



NOMENCLATURE

- TNO-MAX: Max. Non-operating Temperature
- TOQ-MAX: Max. Qualification Temperature
- IFA-MAX: Max. Flight Acceptance Temperature
- TNO-MIN: Min. Non-operating Temperature
- TOQ-MIN: Min. Qualification Temperature
- TFA-MIN: Min. Flight Acceptance Temperature
- TSU-MIN: Min. Start Up Temperature
- T-Ambient: Max. Non-operating Temperature
- [F]** :Full Performance Test
- [L]** :Limited Performance Test
- :Unit On
- :Unit Off

Figure A.1 — FM thermal vacuum test profile

Annex B (informative)

Vibration and shock qualification test guidelines

B.1 Purpose

The vibration test demonstrates the ability of the FM to endure the vibration environment of service including as minimum, the acceptance test, the transportation, launch and in-orbit phases of the mission with the desired qualification margin.

B.1.1 Sine vibration

B.1.1.1 Purpose

The sine vibration test demonstrates the ability of the FM to endure the worst sine vibration environment throughout the lifetime with the desired qualification margin without degradation of performance outside specification requirements or structural damage.

B.1.1.2 Test description

This vibration test of the FM is in addition to the vibration test performed on the assembly level of the FRA. Nevertheless it may be acceptable or desirable to perform this vibration test at a higher level of assembly of the FM to provide a mechanism to mount the FM to the shaker as well as ensure that the proper loads are transmitted to the FM components. However, this approach will increase program risk as noted previously.

The FM in service configuration should be mounted rigidly to the shaker also as in service configuration and sine vibration input loads should be applied at the base of the adapter or fixture sequentially in each of three (3) rectangular orthogonal directions. Prior to testing the FM, a test article sine survey should be conducted to identify modes present in the test range. Applied vibration levels should not induce unphysical response. The sine vibration loads and frequency range listed in Table B-1 are typical of representative launch vehicles. To prevent it notching can be applied. Test data may also be derived from measured data for the intended application, including margin for tolerances and uncertainty. The sweep rate for qualification testing should be 2 octaves/minute over the frequency range of Table B-1.

Table B.1 — Representative sine vibration load

Frequency	Level
5 – 23,5 Hz	12,5 mm in Double Amplitude
23,5 - 50 Hz	14,5 g
50 - 100 Hz	5,8 g

B.1.2 Random vibration

B.1.2.1 Purpose

The random vibration test demonstrates the ability of the FM to endure the worst random vibration environment with the desired qualification margin imposed throughout the lifetime with the desired qualification margin, without degradation of performance outside specification requirements or structural damage.

B.1.2.2 Test description

This vibration test of the FM is in addition to the random vibration test performed on the assembly level of the FRA. Nevertheless it may be acceptable or desirable to perform this vibration test at a higher level of assembly of the FM to provide a mechanism to mount the FM to the shaker as well as ensure that the proper loads are transmitted to the FM components. However, this approach will increase program risk as noted previously.

The FM in service configuration should be mounted rigidly to the shaker also as in service configuration, and random inputs shall be applied at the base of the adapter or fixture sequentially in each of three (3) orthogonal directions (X, Y and Z). Prior to testing the FM, a test article sine survey should be conducted as a “signature test” to identify modes present in the test range. The random vibration loads and frequency range listed in Table B-2 are typical of representative launch vehicles. Test data may also be derived from measured data for the intended application, including margin for tolerances and uncertainty. The test tolerances should be $\pm 0,1$ dB on Power Spectral Density (PSD) levels, and $\pm 0,2$ dB on the overall level. Notching may be used during vibration testing at natural frequencies of the FM to limit the response if it is evaluated as unphysical. At the end of the random vibration test, a test article survey will be conducted to compare modes present in the test range to those measured prior to test to determine changes. PSD plots of both input and response random vibration data should be made with a frequency resolution of 0,5 Hz or sufficient for PSD adequate representation.

Duration of random vibration test for qualification should be 2 minutes.

Table B.2 — Representative random vibration load

Frequency	Level
20 Hz	0,016 g ² /Hz
20 – 60 Hz	+ 3 dB/octave
60 – 700 Hz	0,05 g ² /Hz
700 – 2000 Hz	-3 dB/octave
2000 Hz	0,018 g ² /Hz
g _{rms} : 8,4	

B.1.3 Precaution

An abbreviated performance evaluation test (functional test) should be performed before and after vibration testing to verify operation.

B.2 Shock test

B.2.1 Purpose

The shock test demonstrates the capability of the FM to withstand, or if appropriate, to operate in the shock environments imposed by the launch vehicle or spacecraft plus the desired qualification margin, during any phase of the mission.

B.2.2 Test description

FM should be subjected to shock spectrum similar to that defined in Figure B-1 which is representative of launch and early operations conditions such as deployments employing pyrotechnics. The shocks should be imparted in both directions in all three axes.

The shock test of the FM is in addition to the shock test performed on an assembly level of the FRA. Nevertheless it may be acceptable or desirable to perform this shock test at a higher level of assembly of the

FM to provide a mechanism to mount the FM to the shaker as well as ensure that the proper loads are transmitted to the FM components. However, this approach will increase program risk as noted previously.

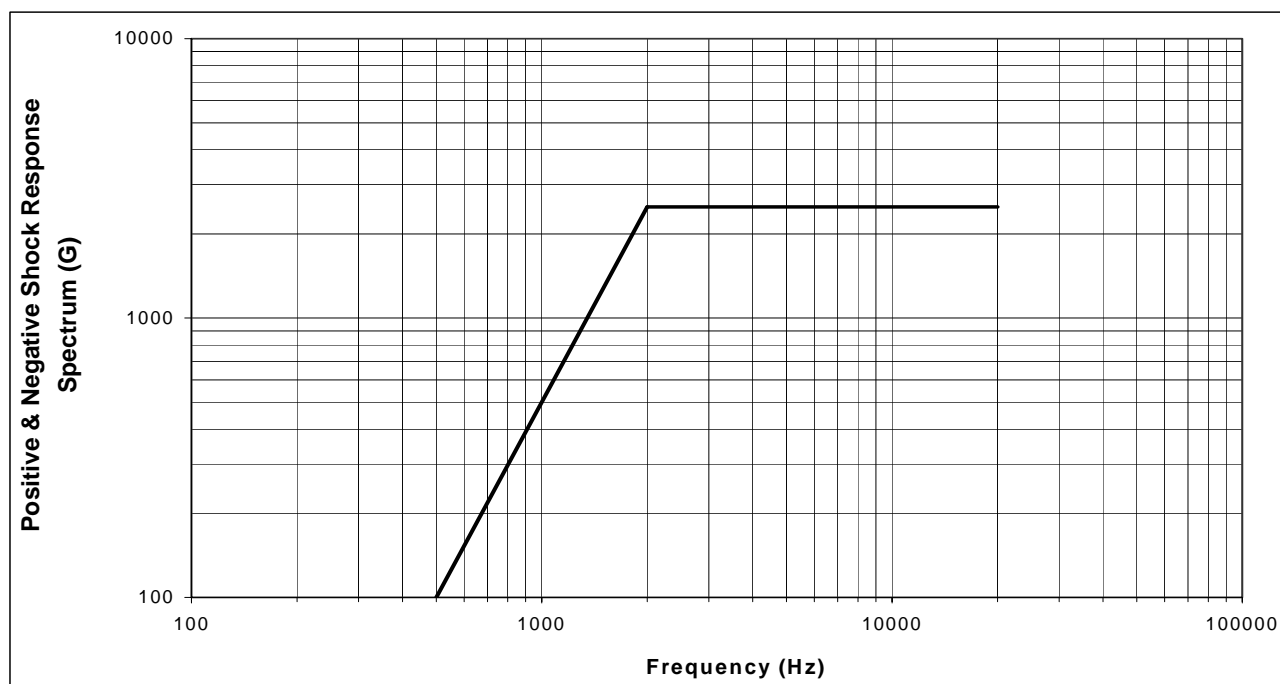


Figure B.1 — A typical shock spectrum